Use of Distribution Bus VAR to Improve Transmission Power Quality

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I. ABSTRACT

This paper reviews the application of an adaptive var compensator to reduce voltage flicker associated with the starting of large motors. The case considered involves the sequential starting of two 2000 hp motors in an across-the-line mode. The motors are served by a dedicated 44 kV-4.16 kV substation. The source 44 kV transmission line also serves over 7000 residential and commercial customers through two widely separated 44 kV-12.5 kV substations. Several methods of reducing flicker were considered. Customer complaints associated with voltage excursions during motor starting were successfully resolved.

Key Words: Motor Starting, Adaptive VAr Compensator, Voltage Flicker, and Shunt Capacitor.

II. INTRODUCTION

Utilities have always faced challenges in meeting the power quality demands of residential and commercial customers while accommodating service to large motor loads. The widely fluctuating reactive power loads imposed by large motors during starting, acceleration and operation can cause fluctuating voltage over a wide area, especially on a relatively weak system. Some of the corrective measures which have been implemented in such situations include:

- Reducing impedance of the delivery point by serving large motor loads from transmission system.
- Installation of dedicated substations for large motor loads.
- Requiring special motor starting systems to reduce initial inrush.
- Installation of series capacitors
- Installation of adaptive Var compensators
- Installation of fast-switched shunt capacitors

The choice of which type of equipment to install depends greatly on local circumstances. The choice is influenced not only by motor starting characteristics, frequency of motor starting, but also by the utility system configuration. Here we attempt to describe the circumstances of an installation and explain why particular choices were made.

The installation addressed in this paper is on the system of Piedmont Electric Membership Corporation (PEMC). Piedmont is an electric cooperative serving approximately 30,000 customers in the central part of North Carolina. These customers are located between Chapel Hill, NC on the southern extremity and the North Carolina-Virginia border. The large majority of PEMC customers are residential with some small to medium commercial customers. The total system load is approximately 125 MW. However, PEMC has served one large petroleum pumping station since 1973. This is the cooperative’s largest single load.

The particular problem encountered is voltage excursions during motor starting at the petroleum pumping station. Motor load at the pump station has remained essentially the same since its initial installation in 1973. However, during the ensuing 30 years, customers served from the same transmission lines have increased their power quality expectations. These customers are no longer simple agricultural loads. They have evolved into dispersed suburban residential loads with home offices as well as agricultural businesses. Many of these customers have high expectations of power quality to support computer systems and automated agricultural processes.

III. UTILITY SYSTEM DESCRIPTION

Piedmont EMC serves the pipeline pumping station through a fifteen mile 44 kV transmission line beginning at their Camp Springs Meter Point. See Figure 1. The meter point is served by a four mile 44 kV transmission line which originates at the Williamsburg Tie Station. The tie station contains a 12 MVA 100 kV-44 kV transformation. The 44 kV system impedance at the Camp Springs Meter Point is approximately 0.88 pu on a 100 MVA base with X/R ratio of 8.

The 44 kV transmission line serving the pumping station also serves two 44 kV-12.5/7.2 kV substations between the Camp Springs Meter Point and the pipeline. Each of these stations serves a typical mixture of residential and commercial loads.

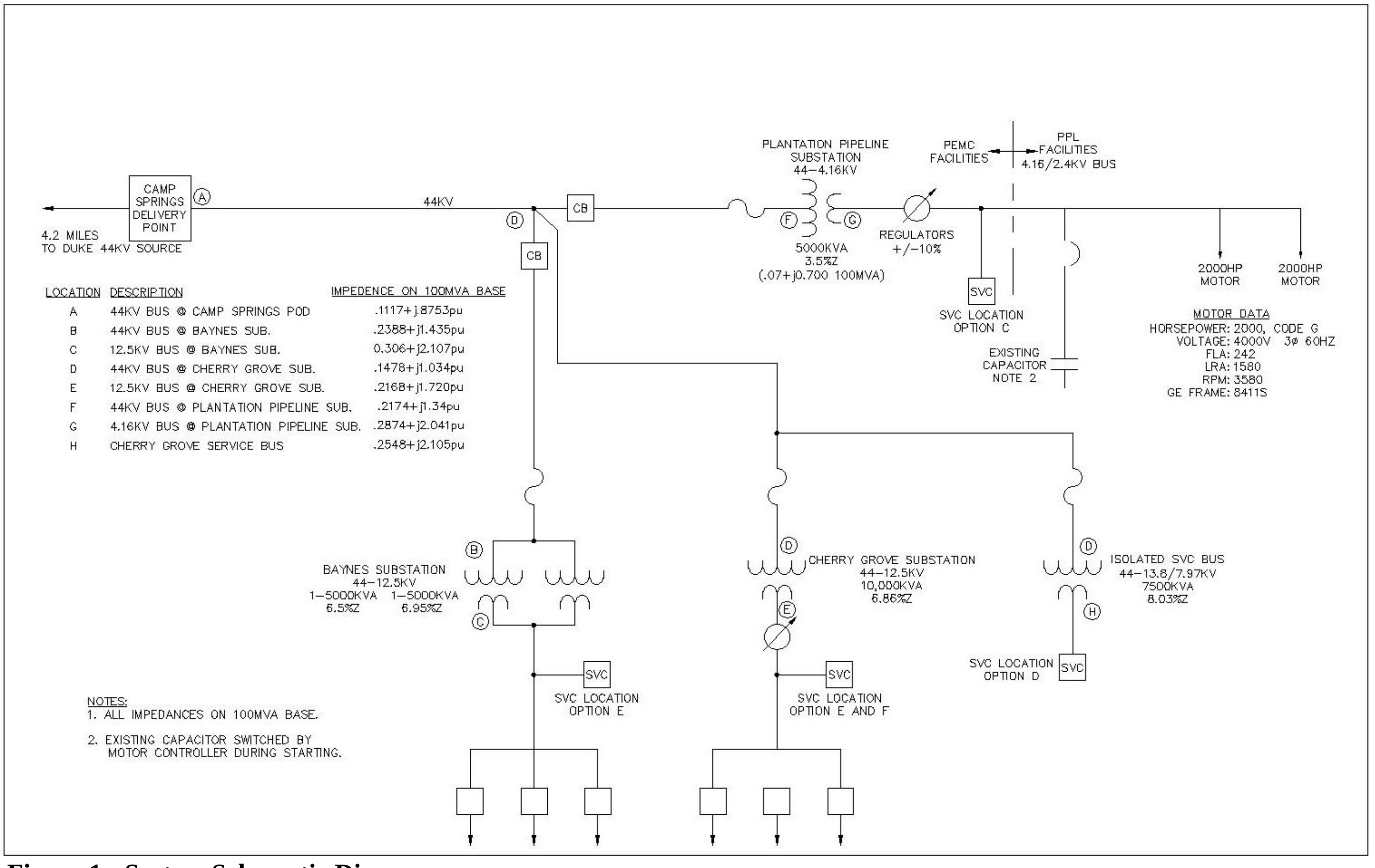

Figure 1 - System Schematic Diagram

IV. MOTOR STARTING PROBLEM DESCRIPTION

A. Customer Complaints

When the petroleum pumping station first began operating in 1973 there were few if any complaints from residential and commercial customers served by the Cherry Grove or Baynes Substations. At that time the motors were being started across the line with no auxiliary equipment to mitigate voltage dips. After the substation had been in service for several years the frequency of complaints did increase. Piedmont EMC and the pump station owner evaluated methods to reduce the amount of flicker on the transmission system. In 1986 the customer installed a fast-switched shunt capacitor on the 4 kV bus serving the motor. This capacitor supplied approximately 8.1 MVAR at a rated voltage of 4160/2400 volts. The capacitor was switched by using auxiliary contacts on the motor starters to bring the capacitor online, hopefully at the same time the motor contacts closed. The capacitor control circuit contained a timer which deenergized the capacitor after the motor had accelerated to running speed. For a variety of reasons this solution met with mixed results.

An important factor driving the decision to install an adaptive Var compensator was the changing nature of the customers served from the two 12.5 kV/7.2 kV distribution stations. Initially these customers were residential and agricultural entities which had relatively unsophisticated power quality requirements. In 1973 the most sensitive device owned by any customer was probably a color television set. Since the motors were started infrequently and at irregular times, the customers did not have a high sensitivity to the voltage dips generated by these occurrences.

While this geographic area had experienced a gradual change in customer expectations, in the 1990's many individuals moving into the area had advanced power quality/reliability expectations. The new customers and the previously existing customers both grew in their expectations with the advent of home computers. These were used not only for increasingly sophisticated agricultural business enterprises but also were used by individuals who were telecommuting and conducting small business operations from their rural homes. Many of the more advanced customers installed uninterruptible power supply (UPS) systems that not only provided backup but also logged each power supply fluctuation. These parallel events of elevated expectations and customer documentation of voltage excursions generated an atmosphere conducive to remedial action by the distribution utility.

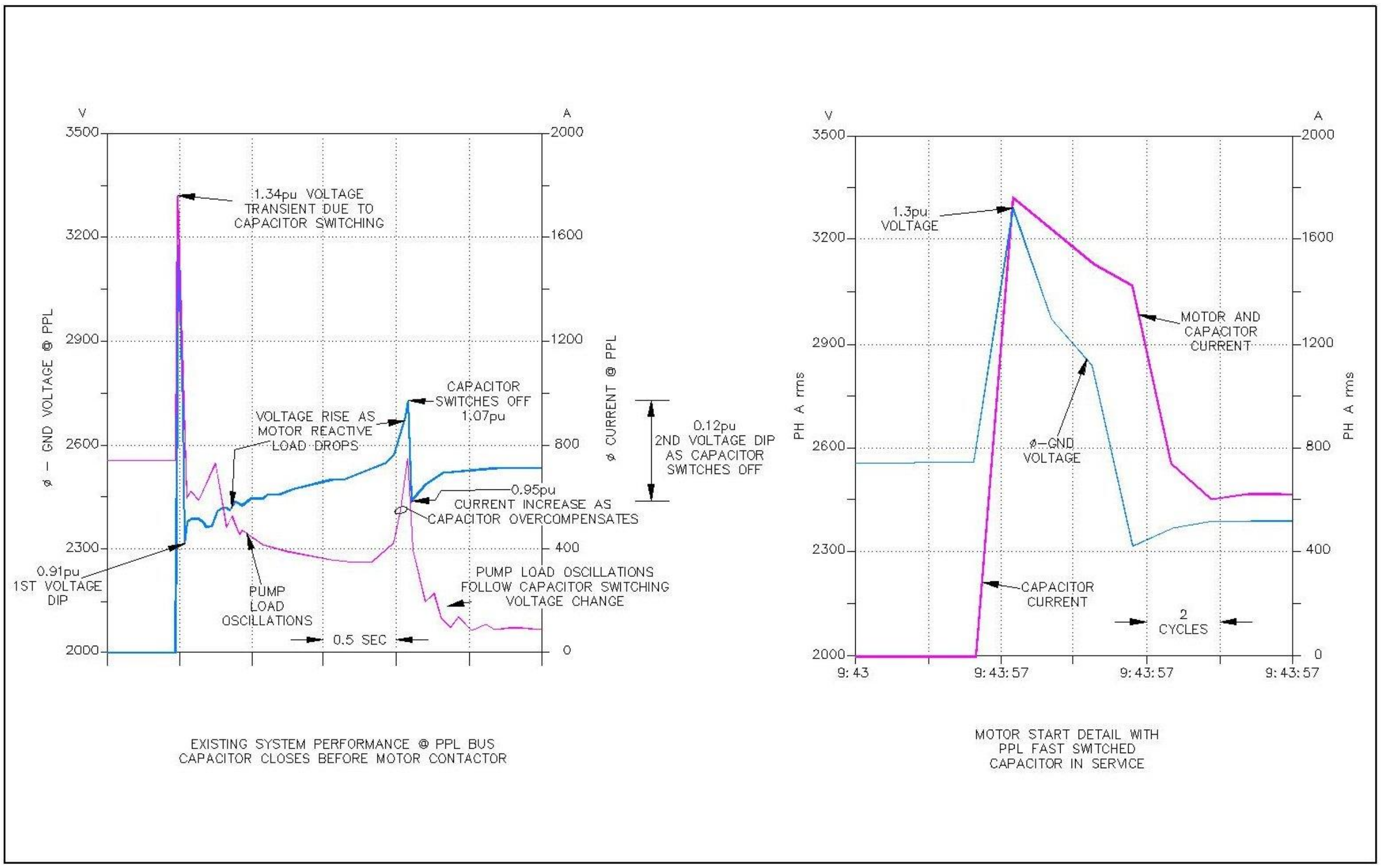

Figure 2 - Motor Bus Voltage and Current with Fast Switched Capacitor in Service

B. Across-the-Line Starting

The two 2000 hp motors in the petroleum pumping station are each started across-the-line. The pumping station is relatively inaccessible from any manned facilities owned by the pipeline company. Therefore, simplicity is mandated in all equipment. Across-the-line starting offers the required simplicity even though it produces greater voltage dip.

Investigation of motor starting characteristics clearly reinforced the engineering assumption of the initial reactive inrush under across-the-line starting conditions. See Figure 2. This produced an instantaneous maximum voltage drop which closely correlated with that expected from conventional inrush calculations. Of course the amount of inrush through the cumulative impedance of the system to the 4 kV motor bus did result in significantly reduced voltage and this in turn reduced the inrush current. In essence, the transmission system acted as a reduced voltage starter.

As shown in Figure 1, the pipeline pumping station motor load is served from a dedicated substation. No other customers are connected to the 4 kV bus. Load inside the pumping station is not sensitive to voltage fluctuations. Therefore, the 19% dip experienced on the 4 kV bus during uncorrected motor starting is acceptable to the customer during normal times. The only starting problems experienced by the pump station were when the cooperative's transmission supplier experienced voltage decline on the 100 kV and 44 kV systems during peak loads. When the transmission voltage received by Piedmont EMC reached the level of approximately 90% of nominal, the 4 kV bus voltage declined to approximately 75% during uncorrected motor starting. As would be expected, this resulted in problems with auxiliary equipment within the pump station. This problem was corrected by installing voltage regulators on the 4 kV bus in order to keep the nominal bus voltage at an appropriate level. See Figure 1. Improvement of the 4 kV motor bus voltage had no constructive effect on the voltage flicker experienced by distribution customers.

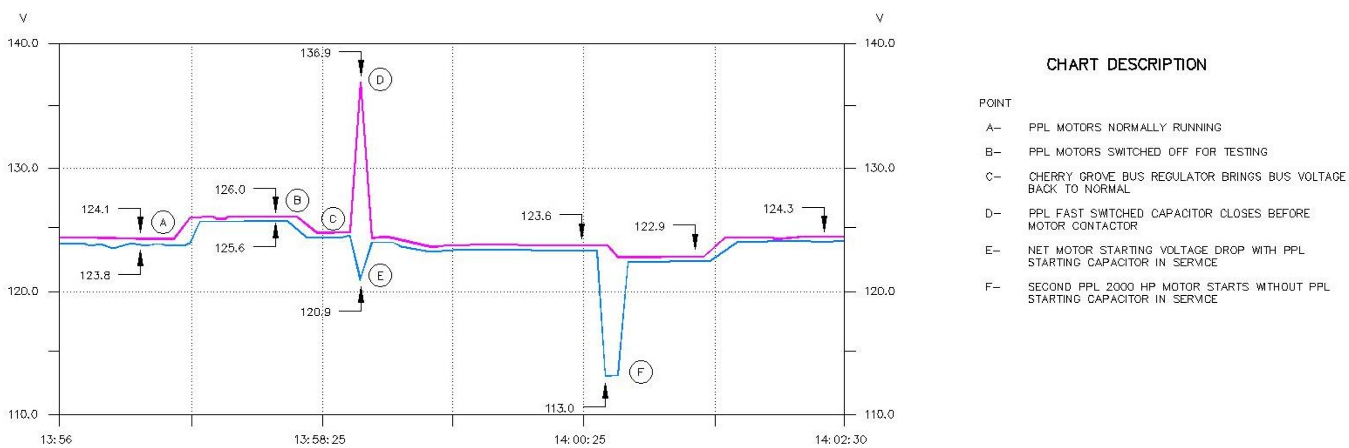

Figure 3 - Distribution Bus Voltage with Fast Switched Shunt Capacitor in Service On 4 kV Motor Bus

C. Previous Remedial Attempts

Piedmont has long recognized the need to improve power quality in the affected area. Discussions with the pump owner had resulted in their installation of a fast-switched shunt capacitor. This unit consisted of 21-200 kVAr capacitor units rated 3000 volts but connected phase-to-phase at 4.16 kV. This produced a reactive compensation of approximately 8.1 MVAR when the 4 kV bus was at rated voltage. However, at the time of initial motor starting the reactive demand for each of the 2000 hp motors brought the 4 kV bus down by approximately 19%. This reduced the effective reactive compensation of the fast-switched capacitor by 35% to approximately 5.3 MVAR. As the motor accelerated, the bus voltage was returned to above normal levels and the reactive compensation provided by the capacitor would increase to approximately 13 MVAR. Since the running power factor of the motors was approximately 90%, this resulted in a highly leading power factor with a consequent voltage rise through the reactance of the transmission system and the 44 kV-4.16 kV substation.

The fast-switched capacitor had several additional deficiencies. First, it was difficult to switch the capacitor on at exactly the time the motor contactor closed and maximum reactive load was created. Failure to achieve synchronized closing results in an uncorrected motor starting dip if the capacitor switch closed after the motor contactor. Conversely, when the capacitor switch closes ahead of the motor contactor there is a significant voltage rise throughout the system until the motor contactor closes.

Second, the maximum demand for reactive correction is at the instant of initial motor energization. The motor reactive load during initial acceleration drops the 4 kV motor bus voltage which reduces the effective compensation from the shunt capacitor bank. As the motor accelerates and less capacitive correction is needed the capacitor increases VAr output, thus raising voltages beyond acceptable levels.

Third, after the motor reached running speed and the capacitor was at its maximum corrective value the capacitor would then be switched off. This produced a strong voltage dip of approximately 12% to all distribution customers served by the transmission line.

Perfect synchronization between the motor contactor and the capacitor switch were never successful. Also, it was very difficult to determine optimum setting for the timer which governed how long the capacitors remained energized. The end result was still voltage dips or significant voltage rises when the motor was energized. See Figure 2 and Figure 3. There was also a very large voltage dip after motor accelerated and the fast-switched capacitor bank was deenergized. These fluctuations were almost as noticeable, and occasionally more objectionable, to customers than simple operation of the motor without correction.

V. DEVELOPMENT OF OPTIONS

The cause of voltage drop during motor starting is the passage of high reactive current through the resistive and inductive components of the system impedance between the current source and the point of measurement. The power factor of the current is a strong determinant of the actual voltage drop experienced. The system dealt with here has an X/R ratio of approximately 7.0 at the point of common coupling. This is the 44 kV bus of the Cherry Grove Substation. Since the voltage drop is proportional to the current passed through the system impedance, it follows that the voltage drop will be reduced by reducing the current.

It is also true that the voltage drop is proportional to the amount of real power (watts) through the system resistance <u>and</u> the amount of reactive power (VArs) passing through the system reactance. It should be noted that the effect of power factor on voltage is dependent on the relationship of the system impedance (inductive vs. capacitive). Specifically, a reactive (lagging) current will produce a voltage <u>drop</u> through a system reactance; while a capacitive (leading) current will produce a voltage <u>rise</u> through a system reactance.

There are essentially two types of system impedances. The simplest is the point impedance such as a transformer. Here the element impedance is a function of the element size, materials and construction. The second type is a distributed impedance such as a transmission or distribution line. Here the element impedance in a function of conductor composition (aluminum, ACSR, copper, etc.), the spacing between conductors, and the length of the element.

From the relationship described above it is apparent that there are several ways to reduce system voltage drop. These include the following:

- Reduce Load Current
- Optimize System Power Factor
- Reduce System Resistance
- Reduce System Reactance

Methods of reducing line impedance include improving conductor conductivity, decreasing conductor spacing or reducing line length.

A. Series Capacitor Installation

In most cases of motor starting flicker the predominant contributor to the flicker is the system reactance. This reactance appears in both the transmission lines and the transmission-distribution transformation. There is also a reactive component in the power supply source impedance. If the series reactance of the system can be matched by a series capacitance, then the reactive component of the motor starting current will create only voltage drop in the resistive component of the system impedance.

Consideration was given to installing a series capacitor on the 44 kV system serving the motor load. In order to achieve benefits from the series capacitor, the installation would have to be made ahead of the first distribution customer tap point. In this particular case the required equipment would have been a 44 kV series capacitor located ahead of the Cherry Grove Substation (Figure 1, Point D). Series capacitors installed on the 12 kV buses would not have created voltage rise during motor starting because the motor starting current would not have passed through these capacitors. Given the protective systems required for satisfactory operation of series capacitors in the 44 kV voltage range, the decision was made to seek other options.

Series capacitors do have the advantage that if they are properly sized they will produce an instantaneous voltage rise that is proportional to the reactive component of the motor starting current. This means that there is no active control system required to measure the amount of capacitance inserted into the system. Sizing of the series capacitor bank is based on the amount of capacitance required to compensate for the system series reactance. The voltage rise across the capacitor bank occurs in response to the flow of load current. This instantaneously corrects for voltage drop through the system series reactance.

Disadvantages of the series capacitor include:

- Limited practicality of fully compensating for series reactance due to the potential for resonance.
- Series capacitors must be designed to withstand voltage rise across capacitors during passage of fault current or,
- Series capacitor bank must be equipped with controls to bypass the capacitor bank during fault events.

Application of series capacitors generally involves one or more of three types of problems. These are:

- Subsynchronous resonance during motor starting.
- Ferroresonance in lightly loaded transformers.
- Motor hunting during operation.

There are solutions to each of these problems but many of the solutions involve an integrated application effort involving both the series capacitor and the motor. Since the objective of any series capacitor installation would be to reduce voltage flicker at the two distribution substation buses during motor starting at the third substation, the capacitor would have to be installed in the transmission line ahead of the point of common coupling for the two types of customers.

Subsynchronous resonance during motor starting is when the motor winding and the capacitor reach a resonant condition at some frequency below the normal operating speed of the motor. The subsynchronous resonance conditions could occur at frequencies between 5 cycles and 20-30 cycles. The occurrence of subsynchronous resonance in motor starting across-the-line would result in the motor never reaching full operating speed. Adverse effects are obvious. These include failure of the motor to operate at designed speed, excessive motor heating, and excessive vibration.

The occurrence of ferroresonance in lightly loaded substation transformers on the load side of a series capacitor installation would have been extremely serious. In this application, two 44 kV-12.5 kV and one 44 kV-4.16 kV transformer banks would have been present downstream from any series capacitor. Various circumstances on utility systems may call for these transformers to be energized with no load on their secondary buses. This circumstance could lead to ferroresonance occurring in the transformer. The risk of this situation occurring was judged to be unacceptable.

Motor hunting during normal operation is generally a problem experienced with synchronous motors and series capacitors. However, motors driving reciprocating loads and pumps could establish a hunting condition with a series capacitor. Although the pumps at the pipeline station are not reciprocating, there is a possibility of hunting occurring due to pressure fluctuations in the long pipeline.

As stated above, all of these conditions have potential remedies. However, such remedies require extensive investigation before installation and constant surveillance under operating conditions. Also, the consequences of any of these three adverse circumstances are severe and could result in completely unsatisfactory conditions for both the utility and the customer. Therefore, series capacitors were not considered as one of the prospective solutions.

B. Modified Motors and Controls

The existing 2000 HP induction motors are equipped with across-the-line starting. Flicker can be reduced by lower motor inrush current during starting. This can be accomplished through a variety of techniques, these include:

- Reduced voltage starting
- Part-winding starting
- Soft start
- Variable frequency drives

Each of these prospective motor modifications has the potential to reduce the voltage dip during starting to acceptable levels. However, each of these modifications also significantly impacts the operating characteristics of the motor. Some methods reduce motor starting torque while others had the potential to adversely affect pump performance. All motor and/or control modifications would require substantial capital investment on the part of the customer. Of even more concern to the customer was the potential for reduced reliability and increased maintenance cost when compared with the existing across-the-line starter. Reliability and maintenance requirements were particularly important to the customer since the pump station is unmanned and in a relatively remote location.

C. Adaptive VAr Compensator at Motor Bus

One of the basic principles of reactive compensation is that the capacitor should be placed as close to the source of reactive load (VArs) as practical. This principle is an obvious truism in the application of capacitors to correct for reactive losses on a distribution system. The application of a static VAr compensator at the 4.16 kV motor bus showed several possible disadvantages. It was known that the 4.16 kV bus voltage dipped approximately 19% at the time of the motor starting. This substantially exceeded the 9% dip on the 44 kV transmission system at the point of common coupling with other customers. Calculation showed that the static VAr compensator could be used to correct for the entire motor reactive starting load. Of course, the AVC could have been sized to compensate for the resistive component of the voltage drop as well. This would have allowed the motor bus voltage to stay at 1.0 pu. While the motor was starting satisfactorily with no compensation, the maintenance of the motor bus voltage at 1.0 pu during starting would have substantially increased motor torque and would have increased the amount of power (kW) drawn through the 44 kV transmission system. In essence, the existing condition was a form of reduced voltage starting for the motor since the bus did fall to 0.81 pu.

A second disadvantage to the compensator application at the motor bus was the 4.16/2.4 kV rating for any compensator which is installed. This would have restricted future application of the compensator to 4.16 kV buses and the utility had no other buses at this voltage level which might require compensation; whereas, a 12.5 kV or a 44 kV compensation system could be applied at other locations on the system of this or similar cooperatives.

It was also unknown the effect that the motor starting torque increase would have on the motor shaft or on the directly connected pumps. The faster pump acceleration may have also had an adverse interaction with the pressure regime in the pipeline.

In view of these concerns, application of a reactive compensator on the 4.16 kV motor bus was considered to be less desirable than some other options.

D. Adaptive VAr Compensator on 44 kV Transmission

Consideration was given to connecting an adaptive VAr compensator directly to the 44 kV transmission line as opposed to installing it on one or more of the 12.5 kV or 4.16 kV buses. This offered some theoretical advantages in that the objective of the capacitor installation was to reduce flicker on the 44 kV transmission system at the point of common coupling with customers served by the 12.5 kV distribution buses. This arrangement would more truly correct the reactive flow through the sections of the system which were causing the voltage drop during motor starting events. Only one ASVC installation would be required. The ideal location for the installation is at Point D on Figure 1.

While there are adaptive var systems operating directly at subtransmission voltages, these are generally applied for system stability. The switching times on typical transmission AVCs are slower and are better suited to meeting stability requirements. The unit cost for transmission AVCs was found to be higher than similar units operating at distribution voltages. One alternative considered was the installation of a distribution voltage adaptive static VAr compensator connected to the 44 kV system through a dedicated 44 kV-12.5/7.2 kV transformer. This would have had the previously mentioned advantages of a single installation connecting at the point of common coupling between the motor load and the distribution customers. However, there was a significant economic disadvantage in that an installation of this type would have required the purchase of a dedicated 44 kV-12.5/7.2 kV transformer. It would have to be a transformer of approximately 7.5-10 MVA capacity.

Another alternative for compensation at the 44 kV level included installation of low voltage static VAr compensators. These units operate at a switching voltage in the 480V-600V range and require transformation even from the normal distribution voltage levels. For instance, a 480V system of this type could have been connected to the 44 kV transmission through either a 44 kV-480V transformation or through series transformation of 44 kV-12.5 kV-480V. The first approach would have required an unusual transformer that would have had a low probability of future use if there was no further need for the ASVC system. The second approach, using series connected transformers of a common configuration, would have resulted in higher initial expense but a greater probability of cost recovery if the ASVC system were abandoned in the future.

E. Adaptive VAr Compensator On Each 12.5 kV Distribution Bus

Since the basic problem was the existence of voltage dips for customers served from the two 12.5 kV buses, the second most desirable technical solution would be to install an AVC on each of the two 12.5 kV distribution buses. The AVCs would operate in response to fluctuations in their respective bus voltages. Control systems were available to operate in this mode. Application of the AVCs at 12.5 kV also would give a high probability of reuse in other locations if conditions changed in this area.

Application at the individual 12.5 kV distribution buses also allows a smaller compensator to accomplish the same degree of voltage correction than a unit located on the 44 kV line. This is because the additional circuit reactance imposed by the 44 kV-12.5 kV substation transformer produces voltage rise due to capacitor switching without having the voltage drop due to motor current passing through the transformer.

Unfortunately, there were several potential disadvantages to the installation of AVC units on each of the 12.5 kV substation buses. These can be summarized as follows:

- The basic installation costs associated with each unit would raise the total project cost compared to approaches that only required a single installation.
- Operation of either ASVC produces a voltage increase at the point-of-common-coupling. See Figure 1. In this particular case, the amount of increase at the point of common coupling would be approximately one-half of the rise created at each of the capacitor controls by its own action. Therefore, the response time of the control system(s) of one (or both) ASVC installations would have to be slowed to avoid feedback interaction between the banks. This slowing of system response was unacceptable since a very fast response was needed to reduce the customer perception of the voltage dip produced by the ASVC on its 12.5 kV bus.

As a result of these negative factors it was decided to evaluate another approach.

F. Adaptive VAr Compensator On One 12.5 kV Distribution Bus

Consideration of the advantages and problems of applying two 12.5 kV distribution bus AVCs led to further consideration of a compromise solution. Conditions were examined for installing a larger ASVC on one of the 12.5 kV distribution buses. It was recognized that the true objective was to improve the voltage variations to the point of customer acceptability. Complete elimination of fluctuations during motor starting was not required. The approach taken was to examine the effect of a larger AVC on one of the 12.5 kV distribution buses. The bank would be sized to create the largest acceptable rise on that 12.5 kV bus during starting of a 2000 hp pump motor. We would then examine the residual fluctuation remaining on the other distribution substation bus. If the residual fluctuation was a net dip, the bank size could be adjusted to equalize the magnitude (absolute value) of the fluctuation on the two buses. This adjustment was judged to produce the optimum solution for all customers. Half of the customers would experience a net rise during the starting event while the other half would experience a dip of equal magnitude.

Calculations showed that an AVC of approximately 8.4 MVAR (effective) could be installed on the 12.5 kV bus at the Cherry Grove Substation (Point E in Figure 1). This would produce a net rise of approximately 2.1% on that 12.5 kV bus and simultaneously reduce the dip on the 44 kV bus at the point-of-common-coupling to approximately 2.6%. Since the Baynes Substation 12.5 kV bus (Point C on Figure 1) experiences the same dip as the 44 kV line at the point of common coupling, this approach would produce a rise of 2.6% on the Baynes 12.5 kV bus. This was judged to be an acceptable compromise.

The advantages of this compromise approach were the following:

- The site preparation and other base costs of the ASVC installation would be approximately one-half that of two installations.
- Economies of scale would reduce price per kVAr of the installation.
- Unit rated 12.5/7.2 kV would be applicable in other locations on many distribution systems.

VI. COST COMPARISON OF AVC OPTIONS

Piedmont EMC solicited proposals from five qualified manufacturers of AVC equipment. Nine proposals were received from four manufacturers for various configurations of AVC systems. It was immediately obvious that the installation of a single AVC on the Cherry Grove 12.5 kV distribution bus would produce the most economical installation while meeting system performance objectives. Comparisons of the four proposals received for this system configuration are given in Table VI-1.

Table VI-1
Compensator Performance and Cost
12.5 kV Single Unit

Vendor	Size	Response Time (mSec)	Step Size (kVAR)	EvaluadedCost (k$)
A	2x4 MVAR	2.5-3.0	N/A*	870
B	2x2/6 MVAR	23-28	N/A*	996
C	8.4 MVAR	11-19	1460	187
D	8.0 MVAR	8	500	325

* Continuous ramping via reactor/capacitor combination.

After a determination that the perceived voltage flicker could be reduced to acceptable levels, PEMC decided that the offering by Vendor C presented the greatest value.

VII. PERFORMANCE OF SELECTED OPTION

After careful analysis in April 2004, Piedmont committed to installation of an 8.4 MVAR, 12.5/7.2 kV compensator on the distribution bus at the Cherry Grove Substation. This is basically the installation described in VI above. Since Cherry Grove Substation also serves as the tap point for a 44 kV transmission line to Plantation Pipeline, this location provided additional opportunities for refinement of the installation. The control system was modified to monitor not only the Cherry Grove 12.5 kV bus voltage but to also monitor current in the 44 kV line feeding Plantation. This allowed the development of control algorithm that instantly responded to motor starting current.

The selected option is described as Vendor C in Table VI-1. This 8.4 MVAR compensator had a step size of 486 kVAR per phase. This permitted voltage resolution of approximately 3.2% during operation. The response time of this unit was quoted as 11 to 19 milliseconds. The obvious cost advantage caused Piedmont to closely consider the suitability of this unit in light of the slower response time and the larger step size.

It was recognized that the relatively infrequent motor starting events constituted a customer perception problem that was substantially different from the repetitive flicker conditions associated with arc furnaces, welders and similar loads. The anticipated operation would be a voltage dip of approximately 13% that would be corrected in less than 20 milliseconds. An appropriate research document was the 1996 publication by the Canadian Electricity Association (Reference 3) that evaluates customer response to changes in luminosity of a 60-watt incandescent bulb. Table VII-1 is based on a 10% instantaneous voltage dip and shows a brightness change of 18% if the voltage is totally restored in 20 ms and an 11% brightness change if the voltage is restored to 95% in 3 msec and to 100% within 20 ms. There was no perceptible brightness change if the 10% dip was restored completely within 3 ms.

Table VII-1
60 watt Incandescent Bulb
Net Brightness Change for 10% Voltage Dip

	Time to 10% Correction (milliseconds)			
	3	**10**	**20**	**30**
10% Dip with Total Correction	2%	11%	18%	24%
10% Dip with 5% Correction in 3 mSec	----	7.4%	11%	14%

It was recognized that the equipment of Vendor C would actually respond with a random distribution of response times within an envelope of 11 to 19 ms. Control design was such that the initial response of the compensator would be with the full 8.4 MVAR capability. This configuration was based on initial measurements which showed the maximum motor reactive current is present at the instant of contractor closure. The Vendor C control was judged to have acceptable response to improve the existing distribution bus fluctuations.

In the fall of 2004 the 8.4 MVAR compensator was installed on the 12.5 kV distribution bus of the Cherry Grove Substation. Availability of the compensator has been excellent with only one outage which was attributable to a controller circuit board problem. Response time has been measured at 1 to 2 cycles. Voltage fluctuations during motor starting have been limited to less than 3% on all distribution buses. See Figures 4A and 4B. Performance to date has exceeded expectations with no customer complaints of voltage dips while the system was in operation.

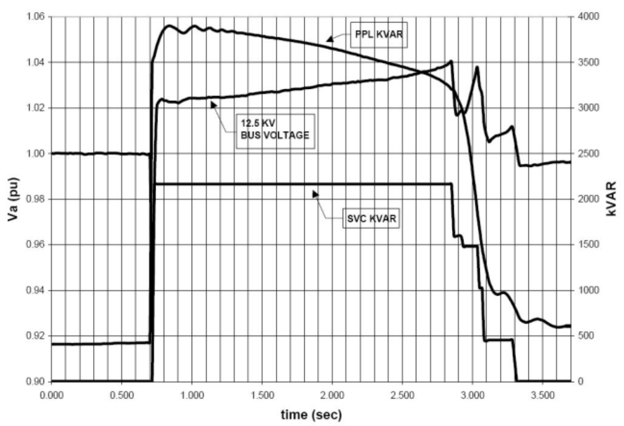

Figure 4A - Motor Start Sequence with Adaptive VAr Compensator in Service
Initial Installation Measurements at Cherry Grove 12.5 kV Bus

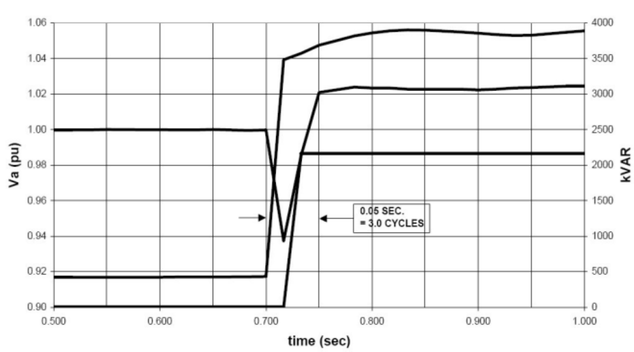

Figure 4B - Detail of Cherry Grove 12.5 kV Bus Measurements Shown in Figure 4A

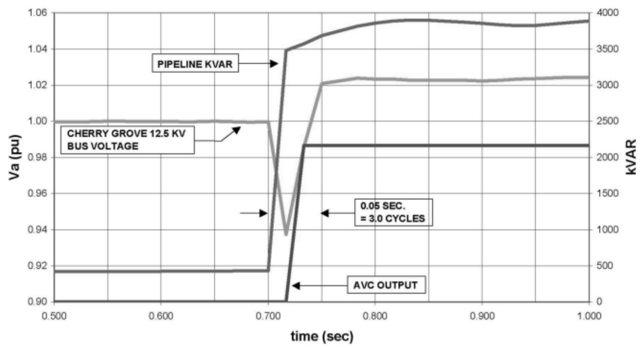

Figure 4C - Detail of Cherry Grove 12.5 kV Bus After Control System Adjustment

VIII. CONCLUSIONS

1. Customer demands for power quality on distribution systems have increased significantly in the past 30 years.

2. Application of fast-switched shunt capacitors is an inadequate solution to voltage dips caused by large motor starting.

3. Installation of an adaptive var compensator for correction of voltage dip due to starting of large motor(s) on a weak transmission system is effective.

4. Effective transmission system voltage stabilization can be accomplished in certain situations by applying var compensator on distribution buses.

5. Response time of reactive compensators varies widely. Customer perceptions of installation success is related to system response time.

6. Cost of compensators varies widely. Matching of compensator system performance to load requirements is required to produce viable system economics.

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